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13. ABSTRACT (Maximum 200 words)

This report results from a contract taskingIoffe Institute as follows: The contractor will investigate materials, architectures and technologies suitable for holographic spectral solutions for aerospace problems. Exploratory holograms will be fabricated in appropriate materials to determine their suitability for particular applications. Holographic spectral filter will be recorded with the selectivity 1-10nm and low out of band transmission. More complicated spectral selective constructions will be considered.

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Final Report
Contract # F617755-98-WE044

"Highly Selective Spectral Optical Elements on the Base of Very Thick Holograms"

Submitted to: European Office of Aerospace Research and Development

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The main goal of the research in the framework of this contract was to develop thick holographic optical elements operating as extremely narrowband spectral filters in the near IR range of spectrum. To fulfil this goal it was necessary to perform theoretical consideration of the problem under development, to choose the most appropriate holographic material for the filter recording and to peform experiments on recording of filters optimized for operation at the specific wavelengths.

1. Theoretical analysis.

The theoretical analysis described in detail in the first interim report and papers [1-3] showed that:

1. In general, reflection holograms are more suitable for recording of highly selective spectral filters. First of all, reflection holograms are more spectrally selective than transmission ones with corresponding parameters. That allows to achieve the desired spectral selectivity using more thin holograms. Besides that, reflection holograms are much less angular selective than transmission ones, that makes them more convenient in operation. And finally, in the reflection configuration, inhomogeneities in depth of both the material itself and of the recorded holographic structure have less influence on the resulting image quality.

2. The thickness of holographic medium, required for the recording of a spectral filter with the selectivity of 1-5 Å, is about 1-2 mm.

3. In the majority of cases a holographic filter being recorded by one wavelength is intended then to operate at another one. If the difference is not very high the main problem is to optimise the operation angle and to minimise the angular selectivity of the device. While the difference becomes considerable, it becomes necessary to adjust the hologram parameters in order to obtain high diffraction efficiency at the desired

operation wavelength. As it was shown in [2], to achieve high diffraction efficiency on the operation wavelength it is necessary to create a higher modulation of the refractive index inside the photosensitive medium than that required for the wavelength of recording. In the case of reflection holograms it can be done through over-exposing the hologram.

2. Recording material.

One of the main problems is to find an appropriate recording medium, since the ordinary holographic materials are up to a few dozens of micrometers thick. Besides that, the recorded hologram must not change its parameters during the postexposure processing (that means no shrinkage) or allow to predict and control these changes with extremely high accuracy. Materials to be used for recording of holographic optical elements are required as well to have high resolution, high transmission at the working wavelength (that means low absorption and scattering losses), they have to provide a long-term stability of characteristics and allow non-erasable playback. The list of candidate materials along with their characteristics was presented in the first interim report. It includes photopolymers (PDA and Reoxan), porous glasses with different fillers and silver glass.

All the photosensitive materials possess to some extent a number of disadvantages, among which the most important for holographic spectral filters are: variations of the mean refractive index during the postexposure processing; shrinkage; nonuniformity in hologram depth of the grating power, mean refractive index and shrinkage. According to our recent results, even small variations of the mean refractive index and shrinkage lead to considerable distortions in the reconstructed image both in phase and in amplitude that causes losses in the reconstructed image resolution. Inhomogeneities in depth of grating power, mean refractive index and shrinkage affect mainly the behavior of the selectivity contour and can lead to its broadening and asymmetry. Basing on the comparative analysis of the materials available we have chosen the PDA photopolymer as the most appropriate one for the recording of holographic spectral filters.

PDA is a medium consisted of polymethylmethacrylate (PMMA) including photochromic quinone molecules. This medium is sensitive in the spectral range 0.44-0.52 μm, that allows to record holograms by the light of Ar laser, and is transparent in the range 0.55-1.52 μm, allowing to record elements for operation both in visible and in near IR. For the PDA photopolymer the ratio of scattered to transmitted intensity is about 0.003. Light losses are mostly due to Fresnel reflections and partly to the light scattering that is shown to be not high. Disadvantages of this material are caused by its photopolymer nature and are as follows: low heat resistance and fairly strong dependence on the environmental conditions, temperature and moisture in particular.

In the second interim report we presented results on the analysis of phenomena affecting the diffraction efficiency of a hologram recorded in this material. It was shown that the diffraction efficiency of holograms reconstructed by a wavelength different from the recording one varies mainly due to the change of reconstruction wavelength according to the Kogelnik's theory for volume holograms and depends

only slightly on spectral variations of the amplitude of refractive index modulation caused by a photographic process creating the phase structure of the hologram.

3. Recording geometry and parameters

Thus, for several reasons reflection configuration is preferable for recording of narrowband holographic spectral filters. As follows from the Kogelnik's formula for reflection holograms, to achieve the maximal diffraction efficiency at the reconstruction wavelength, an "overdeep" recording is required in the short-wavelength region at the recording wavelength.

Diffraction efficiencies of reflection gratings at different wavelengths are connected by a simple relationship:

$$\frac{\eta(\lambda)}{\eta(\lambda_2)} = \frac{\mathrm{th}^2\left(\pi n_1(\lambda)d/\lambda \cos\Theta(\lambda)\right)}{\mathrm{th}^2\left(\pi n_1(\lambda_2)d/\lambda_2 \cos\Theta(\lambda_2)\right)} \tag{1}$$

where $\lambda = 0.514$ μm and $\lambda_2 = 1.06$ μm. According to this formula, to achieve the diffraction efficiency of 90% at λ_2, the diffraction efficiency of the reflection hologram at λ is required to be not lower than 99%.

The spatial period corresponding to the reconstruction of a reflection hologram at angles close to the normal is defined by the formula:

$$\vartheta = \mathrm{acos}\frac{\lambda \cdot n(\lambda_2)}{\lambda_2 \cdot n(\lambda)} \tag{2}$$

where n is a mean refractive index of the medium. For the recording wavelength $\lambda =$ 0.514 μm and operation wavelength in the near IR this condition can be fulfilled only if using the recording schemes with additional prisms and immersion layers between prisms and a sample which provides the optical contact between them.

4. Experimental results.

4.1. Spectral filters optimised for operation at 0.85, 1.06 and 1.5 μm.

Figure 1 presents experimentally measured contours of spectral selectivity for the filters optimised for 0.85 and 1.5 μm. The diffraction efficiency of these samples is not very high: about 80% for the one for 0.85 μm and 62% for 1.5 μm. Besides that both the contours have profound side lobes. These side lobes resulted from insufficient apodization of initial samples. Some more experiments are required to optimise the procedures allowing to obtain strictly apodized contours. The spectral selectivity of these holographic filters is 0.7 Å and 1Å respectively.

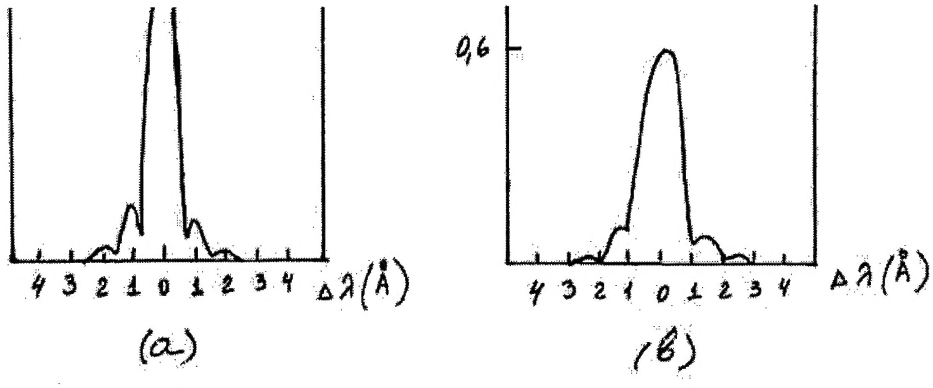

Figure 1. Spectral selectivity contours of holographic filters optimised for operation at 0.85 μm (a) and 1.5 μm (b).

Filters optimised for 1.06 μm have been used for studies of the hologram dynamics in recording and amplification stages in this wavelength range. The experimentally observed dynamics of recording is practically identical to that at the usual conditions. The only difference is the lower exposure time (for layers of a same thickness and with equal concentrations of photoactive compound) due to the rise of effective thickness of the layer. After the amplification and fixing the diffraction efficiency of a hologram operating at 0.514 μm achieved the magnitude of 98%, that had to correspond to the efficiency of the order of 75-80% at 1.06 μm. The direct measurements of the hologram efficiency by the Nd laser light at 1.06 μm gave the magnitudes of 75±5% for different holograms. The angle between the incident and diffracted beams varied for these samples within the range 3-9°.

4.2. Two reflection gratings designed for simultaneous reconstruction of two wavelengths.

There are specific tasks requiring combined filters able to operate at two different wavelengths (usually one of which is in visible and another in IR). We tried to find a holographic solution to this problem.

The hologram recording with the exposure close to or exceeding the one required for a complete bleaching of phenantrenquinone in the maxima of interference structure results in a deviation of the refractive index profile from the sinusoidal distribution, that is equivalent to an appearance of harmonic components with spatial frequencies multiple to the basic one. Amplitudes of these components can be fairly high. Seemingly, an elegant method of the creation of a "double-frequency" spectral filter could be to record an overexposed hologram for a basic frequency, in which an ideally adjusted one with the double spatial frequency would appear. However, such an automatic correspondence does not work due to the dispersion of refractive index: the

filter diffracts the basic frequency and harmonic at different angles. Another way to obtain a spectral filter operating simultaneously at two different wavelengths is to record two superimposed gratings.

This part of work was connected with the superposition on the recorded grating optimised for 1.06 μm of another grating for the second harmonic: 0.53 μm. As follows from the experimental dependence the recording of a second, superimposed grating is connected with the rise of exposure time that is caused by the decrease of effective absorption of the layer (due to the deplete of working substance) and change of recording geometry (recording without additional prisms). The dynamics of hologram rise at the diffusion amplification is higher than that for the hologram at 1.06 μm. A very interesting fact is that at the superposition of a fairly efficient hologram (in some cases the diffraction efficiency of a hologram at 0.53 μm was about 80%) the parameters of a hologram at 1.06 μm were practically the same as in the case of a single hologram. It is also worth noting that to provide the simultaneous reconstruction of the two wavelengths it is necessary to achieve in experiments on holograms superposition an accurate coordination of recording angles for the two gratings, with regard to the wedge shape of recording layers.

5. Filter operation.

To obtain a successful result it is necessary not only to fulfil all the requirements for optimal recording of the holographic grating itself but also to analyze potential effects that can influence parameters of the filter during its operation and minimize such an influence. These effects are caused mainly by material/hologram behavior in the environmental conditions including varying conditions as well.

As every wavelength selective system which operation is based on the phenomenon of interference, the holographic filter is affected by the environmental temperature. Temperature variations cause variations of the spacing in the recorded interference pattern causing the change of the Bragg operation wavelength or angle. Adjusting the temperature or slightly tilting the filter one can tune the selector to the desirable wavelength in the certain environmental conditions. Quantitative characteristics of this dependence are connected among other parameters with the element construction. It was shown that if the polymer medium is not coated or is coated by polymer plates, the dependence is weak: spectral maximum shifts in 0.15 Å with 1 degree C. But if the polymer filter is coated by glass plates (such a construction makes it more rigid and protected from humidity) the dependence is more strong: the temperature shift is 0.5 Å/degree. Such a difference has been explained by photoelastic effects occurring because the thermal expansion coefficient of polymer is much greater than that of inorganic glass.

Thus, during 1 year of the contractual effort we have performed:

1. The analysis of spectral selectivity of volume holograms depending upon hologram parameters (layer thickness, spatial frequency of the recorded grating) and recording geometry for both reflective and transmissive holograms.

2. The comparative analysis of available thick holographic media suitable for recording of holographic spectral selectors for operation at near IR range of spectrum.
3. The analysis of effects affecting the hologram diffraction efficiency when the reconstructing wavelength differs noticeably from the recording one.
4. The analysis of the refractive index modulation required to record a highly efficient holographic spectral filter operating at the wavelength different from the recording one.
5. The experimental recording of the filters operating at 0.85, 1.06 and 1.5 μm.
6. The experimental recording of a combined filter operating at 0.53 and 1.06 μm simultaneously.
7. The analysis of filter operation at environmental conditions.

The results obtained were presented and published in the proceedings of the following conferences: Photonics West'99 in San Jose, CA, ([2]), Aerosense'99 Orlando, FL ([1]) and ICOSN'99 Yokohama Japan ([3,4]). The paper [5] will be presented at Photonics West'2000 in San Jose, CA.

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